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In-plane field angle dependence of the critical current of *R*BCO wires at low temperatures

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Abstract

The dependence of the critical current (I_c) of an *R*BCO superconductor on the angle of a magnetic field applied within its basal plane (coplanar with the transport current) is commonly held to follow a variable Lorentz force behavior. I_c varies trigonometrically from some maximum value determined by flux-line cutting or other effects in the force-free configuration of field parallel to current to its minimum value in the maximum Lorentz force configuration of field and current perpendicular. The reduction in I_c is considered to result from the increasing depinning force exerted by the current on the flux lines as their relative directions diverge.

Here we show, for contemporary *R*BCO-based coated conductor wires, that this presumed behavior is only evident at high temperatures, notably including 77 K. At lower temperatures as high as 60 K in moderate magnetic fields (8 T), significant deviations from the expected behavior are observed, becoming stronger to lower temperatures and higher fields. An intermediate behavior of doubled periodicity is observed, incompatible with the simple trigonometric model, and around 30 K, 3 T this resolves into a fully inverted behavior, with maximum I_c obtaining in the maximum Lorentz force configuration and minimum I_c in the force-free configuration.

These experimental results have important implications for the design and operation of *R*BCO-based devices in the common operating regime of low temperatures and intermediate to high fields. In particular, it is commonly assumed that the maximum Lorentz force configuration is always the configuration of minimum I_c. In fact, we show here that this is not the case, with I_c values up to 30% lower being observed in the force-free configuration.

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Keywords: *R*BCO coated conductors; critical current anisotropy; in-plane magnetic field; variable Lorentz force

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1. Introduction

The complex, highly anisotropic and unpredictable dependence of the critical current (I_c) of pinning-engineered *R*BCO wires on the applied magnetic field and operating temperature presents a major challenge to the design of superconducting devices utilizing these materials [1,2]. Indeed, the difficulty of coil design with wires having this I_c behavior is one reason manufacturers continue to use BSCCO wire [3] in preference to *R*BCO.

With over-estimation of I_c being potentially catastrophic for superconducting devices, the existence of this strong I_c anisotropy often leads to significant over-engineering through the adoption of a "minimum I_c" parameter in the design. With wire price typically the largest single contributor to the cost of such devices, this is detrimental to the economic viability of large-scale *R*BCO-based technologies [4], in spite of the many technological advantages they offer. More efficient usage of available wires can be achieved, but this requires more advanced design methodologies [5] incorporating the full experimental I_c profile of the specific wire to be used. Such approaches have been successfully applied to the design of complex superconducting devices [6].

Whilst it is commonplace to characterize the out-of-plane anisotropy of *R*BCO-based wires at 77 K, we have been arguing [7,8] that characterization at the operating temperature of interest is critical to a robust design, with no general scaling law available – or even possible – to reliably relate 77 K behavior to low temperature performance. However, routine characterization at the lower temperatures applicable to magnets and rotating machines is rather uncommon due to the relative expense and difficulty of achieving these temperatures.

Even less common is the investigation of the in-plane anisotropy of the wire. Where such studies have been undertaken, the experiment is almost universally conducted at 77 K or above [9–13]. The justification for this, besides ease of measurement, stems from the inherited understanding that the in-plane behavior exhibits a "Lorentz force variation" whereby the minimum I_c is observed for the applied field perpendicular to the current [13], and therefore that any in-plane component of the applied field only serves to improve wire performance. Here we argue that flux pinning is as decisive in determining the in-plane variation in I_c as the out-of-plane, and therefore that the inherent unpredictability of behavior persists rendering actual measurement crucial. That this is at least feasible has already been shown by investigations of the decisive influence of twin boundary pinning on the in-plane I_c variation [14].

In this paper we present initial measurements of a commercial YBCO wire that exhibit a systematic deviation from the expected in-plane Lorentz force variation at low temperatures. At typical operational temperatures of around 30 K, we show that the I_c in the maximum Lorentz force configuration of field perpendicular to current is *higher* than that in the force-free configuration of field and current parallel. This is crucial information for device designers, who may otherwise overestimate I_c in sections of wire that experience a longitudinal field component.

2. Experimental

Transport critical current measurements of a full wire sample of Amperium® wire obtained from American Superconductor, Inc. were performed in a custom high-current I_c measurement system described fully elsewhere [15]. A dedicated in-plane sample holder was constructed to enable horizontal rotation of the sample within the transverse field of the 8 T HTS magnet. A closed-cycle helium gas circulation and cryo-cooling system enabled stable sample temperatures down to 25 K to be reached. Voltage taps were soldered to the 4 cm long wire sample at a spacing of 5 mm, and an electric field criterion of 1 μV/cm was used in determining I_c from full *IV* curves obtained up to 850 A.

3. Results and discussion

Figure 1 summarizes the new experimental results obtained in this work. For the representative field of 5 T, at the commonly-observed temperature of 77.5 K, a behavior reminiscent of much published work is obtained, with a maximum I_c value obtained in the force-free configuration of field parallel to current direction ($\phi = 0°$), dropping to a minimum value in the maximum Lorentz force configuration of field and current perpendicular ($\phi = 90°$).

It is immediately apparent, however, that on investigation at a lower temperature of 25 K – within the temperature regime commonly adopted for moderate-field coil applications – this behavior is fully inverted. Now the *maximum* I_c is obtained in the maximum Lorentz force configuration, dropping to a minimum in the force-free configuration. The usual assumption that the I_c obtained for the maximum Lorentz force configuration is a minimum in the plane will in this case overestimate the I_c of the wire under these operating conditions by almost 40% (570 A versus 410 A).

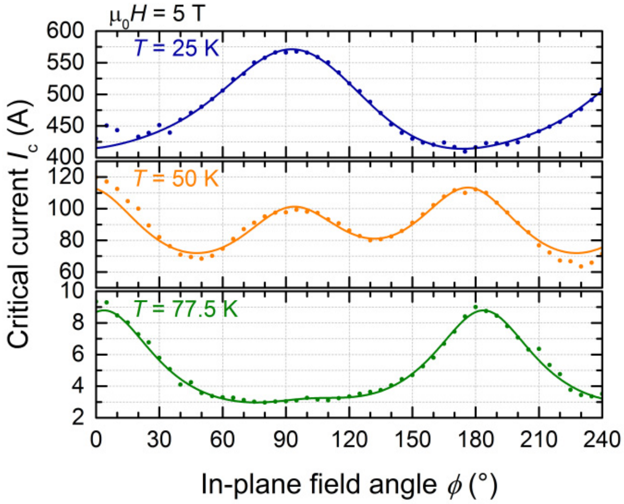

Fig. 1. Evolution of the in-plane field angle dependence of the critical current of *R*BCO wire to low temperatures at a representative field of 5 T. $\phi = 0°$ is the field applied parallel to the current direction (the force-free configuration); $\phi = 90°$ is field and current perpendicular (the maximum Lorentz force configuration). Solid lines are maximum entropy models of the data as discussed in the text.

It is broadly acknowledged that the theoretical treatment of type II superconductors in magnetic fields having a component parallel to the current direction remains under development [13]. A recent survey and extension of proposed theories [13] ascribes the limitation of I_c in the force-free configuration to a value below the self-field value to flux-line cutting, and provides that this introduces a second parameter into the geometrical dependence of I_c that is governed by the varying Lorentz force:

$$I_c(\phi) = \left(\frac{\sin^2\phi}{I_{c\perp}^2} + \frac{\cos^2\phi}{I_{c\parallel}^2} \right)^{-1/2} \tag{1}$$

Here, the first term represents the behavior due to the varying Lorentz force (providing the limiting value of $I_{c\perp}$ when $\phi = 90°$), while the second term incorporates the I_c-limiting effects of flux-line cutting in the vicinity of $\phi = 0°$. This expression can accurately fit both the 77.5 K data and the 25 K data shown, and it would be feasible to suggest by extension that it describes the behavior in both cases, with flux cutting effects coming to dominate over flux pinning at the lower temperature. However, this interpretation is not without its difficulties.

Our additional dataset acquired at 50 K belies this interpretation, however. In this intermediate temperature regime, a combined behavior of doubled periodicity is observed that cannot be explained in the context of the above theoretical framework or equation 1. Neither I_c limitation by flux pinning nor by flux cutting can produce this complex behavior with minimum I_c at an intermediate angle, and we must therefore question whether they are appropriate explanations for the behavior in the two limiting cases either. Instead, we revert to our generally-applicable maximum entropy modelling approach [16] to describe the angular variation in I_c using a sum of angular Lorentzian components:

$$I_c(\phi) = \frac{I_0\,\Gamma}{\cos^2\phi + \Gamma^2 \sin^2\phi} \tag{2}$$

where I_0 is the amplitude of the component and Γ is a width parameter. Fits to this function produce the solid lines plotted on figure 1, with the component parameters listed in table 1.

Table 1. Maximum entropy component parameters of the in-plane $I_c(\phi)$ data at different temperatures.

Component parameter	77.5 K	50 K	25 K
0° angular Lorentzian amplitude	4.2	50	88
90° angular Lorentzian amplitude	0.55	40	390
Shared width	0.50	0.55	0.78

It is seen that all the datasets are well modelled by two angular Lorentzian components centered at approximately ϕ = 0° and ϕ = 90° (without any uniform offset). In the intermediate temperature regime, it is unsurprising that two components suffice to model the data. What is of interest is that the widths of the two components can be constrained to be equal (mostly falling within the error of the fit), suggesting a reduction in the total number of free parameters required to describe the data to three. This would be consistent with the number of parameters required to fit a single component and a uniform offset to the data at the extremes of temperature, although it is undeniable that a better fit is obtained at 77.5 K by admitting a low-amplitude angular component (of equal width) near ϕ = 90°. We have previously described observing this emergent self-reduction in free parameters [17] across diverse datasets, and consider this as strong evidence for a consistent underlying mechanism dictating the in-plane I_c behavior across the full temperature range; however, we defer a fuller exposition of these results to a complete analysis of the entire dataset.

4. Conclusion

We have reported, for the first time, experimental data obtained at low temperatures on commercial YBCO wire showing a systematic deviation from the commonly-reported Lorentz force variation in critical current for magnetic fields applied in different in-plane directions relative to the current flow direction. These deviations begin to arise at temperatures as high as 60 K in moderate magnetic fields (8 T). At the lowest temperatures studied, a complete inversion of the expected Lorentz force variation in I_c is observed, with the result that the wire I_c with the in-plane magnetic field applied in the maximum Lorentz force direction may be as much as 40% higher than that with the magnetic field applied in the force-free direction.

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